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Magnetic Alloys of Iron, Nickel, and Cobalt[1]

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SYNOPSIS: Recent investigations of magnetic properties of alloys of iron, nickel and cobalt have resulted in the discovery of materials of remarkable magnetic properties previously unknown. In a brief review, early experiments that led to the discovery of these materials and the magnetic properties of the entire field are discussed. Those groups of alloys of outstanding scientific and technical importance such as the permalloys and the perminvars and special heat treatment required for development of special magnetic properties are taken up in detail. A theory is suggested to account for some of the magnetic characteristics, and a few of the practical applications of these materials are described.

IF the three ferromagnetic metals—iron, nickel and cobalt—are melted together in various proportions, all of the resultant alloys are magnetic when the materials used are reasonably pure. The magnetic properties of the alloys, however, vary greatly with composition and heat treatment. Some alloys have been found to be nearly non-magnetic; others have higher permeability than any hitherto known magnetic material and may be magnetically saturated in the earth's field. Still others are superior at high field strengths or excel in constancy of permeability at low fields.

In the Bell Telephone Laboratories we have been especially interested in these alloys and have made a fairly complete survey of the magnetic properties of the whole field of compositions of these metals. In this address I wish to tell you how our interest in those alloys was aroused, what our procedure was in carrying out the investigation, and what some of the principal results were. I shall also refer to some of the particular applications which we have made as a result of our discoveries.

I first became interested in these alloys in 1913. At that time I was looking for a magnetic material which would be more suitable for certain uses in the electrical communication field than the iron then used. Of the large number of alloys investigated, several contained principally iron and nickel. One of these was particularly interesting. The composition of this alloy was approximately 70 per cent nickel and 30 per cent iron; it was a commercial alloy used as a special resistance material. In the hard worked condition in which it was

[1] *Journal of the Franklin Institute*, Vol. 207, May, 1929, pp. 583–617.

supplied, its magnetic properties were not even as good as iron in a similar magnetic condition, but when heat treated it was superior to the iron at low field strengths, the region in which I was especially interested.

This alloy differed from iron in another important characteristic. Experience with iron had shown that the best magnetic quality was obtained when the material was heated to a high temperature, and then cooled slowly to room temperature. It was considered particularly important to cool slowly in order to give the iron time to pass through its transformations and to allow it to build up a large grain structure. When the nickel-iron alloy was heat treated in this manner, it was found to have lower permeability than it has when cooled fairly rapidly.

The discovery that rapid cooling was required for this alloy to give the best magnetic quality was one of the major contributions from our early work. It showed us that one of the important factors in developing the magnetic properties of new alloys was the determination of the rate of cooling for the best magnetic quality for each alloy.

Another difference between this alloy and iron relates to the energy loss caused by the hysteresis at low flux densities. In this range iron has lower hysteresis loss when it is in a mechanically hard condition than when it is well annealed. As the flux density increases, however, the hysteresis loss of the hard material increases more rapidly than does that of the annealed and at medium and high flux density, the mechanically hard iron is much inferior. Tests on the nickel-iron alloy show that both for high and low flux densities the hysteresis loss was a great deal higher for the mechanically hard material than for the one heat treated to give the best magnetic quality.

The discovery of the unusual magnetic properties of this 70–30 per cent nickel-iron alloy gave us the lead that we were looking for, and started our investigation of the magnetic properties of the whole series of nickel-iron alloys. We found, as we had reason to expect, that the 70–30 per cent alloy was one of a large group of alloys in the same series which had similar magnetic properties. In fact substantially all of the alloys containing more than 30 per cent nickel had similar characteristics except that some of them were not as sensitive to heat treatment as the first alloy we had tested.

Because of the technical possibilities of the nickel-iron alloys, we spent several years in their investigation and their commercial application. We were especially concerned with increasing the resistivity of a number of these alloys, and with this in view we added other

elements to the iron and nickel in order to determine their effect both on the resistivity and the magnetic properties. Copper, chromium, molybdenum, tungsten, and tantalum are a few of those we added; also the magnetic element cobalt. The striking results obtained with the addition of cobalt to the iron-nickel alloys led us to make a com-

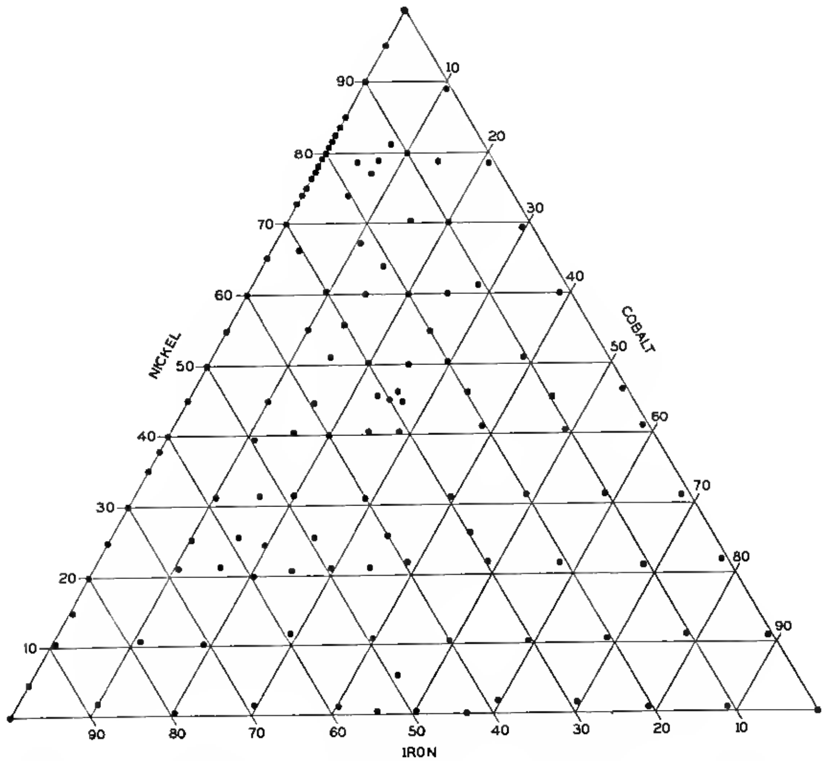

Fig. 1—Composition diagram—Ni-Fe-Co series. Dots show compositions tested.

plete survey of the whole field of alloys containing the three magnetic metals.

A convenient way of showing graphically the number of alloys we investigated and the distribution of compositions of these alloys is afforded by the equilateral composition triangle in Fig. 1. In this triangle the metals—iron, nickel, and cobalt—are represented by the corners; the binary alloys by points on the three sides, and the ternary alloys by points within the area of the triangle. Each alloy we investigated is indicated by a dot and the location of each dot indicates the proportion in per cent of the three metals in the alloy. A glance

at the diagram will give you an appreciation of the completeness with which the field was covered.

In preparing these alloys we used the best commercial materials available. These contained small amounts of impurities, some of which affect unfavorably the magnetic properties. It was considered beyond the scope of this investigation, in which such a large number of alloys were required, to attempt to remove these impurities completely or even partially. Moreover we were especially interested in alloys which could be reproduced on a commercial scale, without too great cost due to refinements of raw materials or to methods of preparing the alloys.

Throughout the investigation we have followed a standard procedure for preparing our samples. We have also followed a standard procedure for heat treating and in magnetic measurements. The result is that we have accumulated a large mass of data over a number of years, all of which may be significantly compared.

The alloys were cast from Armco iron, electrolytic nickel, and a very high grade of commercial cobalt containing only small amounts of impurities. They were melted together in the desired proportions in a silica crucible in a high frequency induction furnace. The metal was cast into bars 18 in. long and ¾ in. in diameter. The bars were rolled or swaged into ¼ in. rods; then they were drawn into wire and flattened and trimmed into ⅛ in. by .006 in. tape. The material was annealed several times in the reduction process, for the cold working hardened the alloys rapidly and made them difficult to work.

To prepare the tape for heat treatment and subsequent magnetic measurements, about 30 ft. of it was wound spirally into a ring of 3 in. inside diameter, the ends being spot welded to the adjacent turns. Care was taken to wind the rings loosely to prevent the turns from sticking to each other during annealing.

For convenient comparison of the magnetic properties of the alloys with those of the metals from which the alloys were cast, sample lots of the iron, nickel, and cobalt which we used in making the alloys, were melted, cast, and prepared in the same manner as the alloy test samples.

In Fig. 2 the various steps through which the alloys had to pass in the mechanical reduction to tape are shown. Between each step in the reduction, as indicated by a sample, the alloy had to be annealed to remove the mechanical hardness. A sample ring wound from the finished tape, ready for heat treatment, is also shown in the figure.

The next step in the process of preparing these alloys for magnetic measurements is the heat treatment. Early experience with the

nickel-iron alloys indicated the need for a variety of such treatments, but of course it was impossible to apply to every alloy such a complete variety of heat treatments, that all of the combinations of heat treatment and composition could be known. Our procedure was to apply three types of heat treatment.

A number of rings of a given composition were packed in a nichrome pot. The pot was placed in an electrical resistance furnace, the temperature of the furnace raised to between 900° and 1,000° C. and held at that temperature for one hour. The current was then turned

Fig. 2—Cast alloy bar and intermediate stages of samples in reduction to tape. Also ring from tape ready for heat treatment.

off and the pot cooled with the furnace. Ten hours were required for the furnace to cool to the temperature of the room. Between 700° C. and 400° C. the rate of cooling was approximately 1.5° C. per minute.

At least two rings of each composition were always annealed together. One of these rings received no further heat treatment. The second ring was heated for 15 minutes in a furnace held at 600° C., then removed and cooled rapidly on a copper plate in the air. With this cooling the rate was approximately 20° C. per second. In some cases a third annealed ring was heated 24 hours at 425° C.

In the discussions and in the figures, the rings which received the first heat treatment only are referred to as "annealed," those reheated to 600° C. and rapidly cooled as "air quenched," and those held for a long time at 425° C. as "baked." The magnetic measurements were made on these rings.

The magnetic induction, or flux density, was determined for a large number of magnetizing forces, beginning at a few thousandths of a gauss and increasing in uniform steps up to 100 gauss. Magnetization curves were plotted from these measurements. The induction was also determined for each composition at a magnetizing force of 1,500 gauss.

The permeabilities were computed from the induction measurements,

and were plotted either against the flux density or the magnetizing force, depending on which graph illustrated best the characteristics of the material. At the lower ends these curves were extended to zero field strengths. Their intercepts on the permeability axis are the initial permeabilities. The maximum permeabilities were also obtained from these curves.

For determining hysteresis loss, two methods were used. In some cases hysteresis loops were plotted from ballistic measurements, and in other cases a direct determination of hysteresis loss was made from the apparent alternating-current resistance of a winding wrapped around the sample. Ordinarily the hysteresis loop was obtained for one condition only in which the flux density was varied between plus and minus 5,000 gauss. For some of the alloys of special interest, a large number of loops were obtained for different magnetizations, the maximum flux densities varying from 100 or less to 5,000 gauss.

In illustrating the magnetic properties I will be forced to limit the discussion to a few outstanding values for each alloy, and by comparing these, obtain a general view of the relation of the magnetic properties to composition. The values I have selected are the intrinsic inductions for two magnetizing forces, 50 and 1,500 gauss respectively, the initial and the maximum permeabilities and the hysteresis loss for a maximum flux density of 5,000 gauss. For a number of alloys which represent regions of composition with magnetic properties of special interest, curves for magnetization and permeability will be shown. A number of hysteresis loops for different maximum flux densities will also be given.

In illustrating graphically the relations between the magnetic properties and compositions of ternary alloys, it is convenient to plot these quantities in the form of solid diagrams. Such a diagram is shown in Fig. 3 constructed for initial permeabilities of the alloys in the annealed condition. In this figure the composition triangle, Fig. 1, is used as the base. On this triangle, verticals are erected proportional to the numerical values of the initial permeability. The ends of these verticals give a contour of the upper face of the figure. With a sufficient number of alloys this surface represents fairly accurately the values of the initial permeabilities for all compositions. The edges of the surface give the initial permeabilities of the binary alloys and the rest of the surface those of the ternaries.

The coordinates of the composition triangle, the intersections of which give the compositions of the alloys in 10 per cent variations, are projected to the surface and are represented by the narrow black lines. The heavy black lines on this surface are contours such as

you see on topographical maps and represent the intersections with the surface of planes parallel to the base at definite elevations. Each line locates the compositions of those alloys which have equal values of initial permeability.

In this solid diagram of the initial permeabilities for the alloys in annealed conditions, there are three regions of composition which are

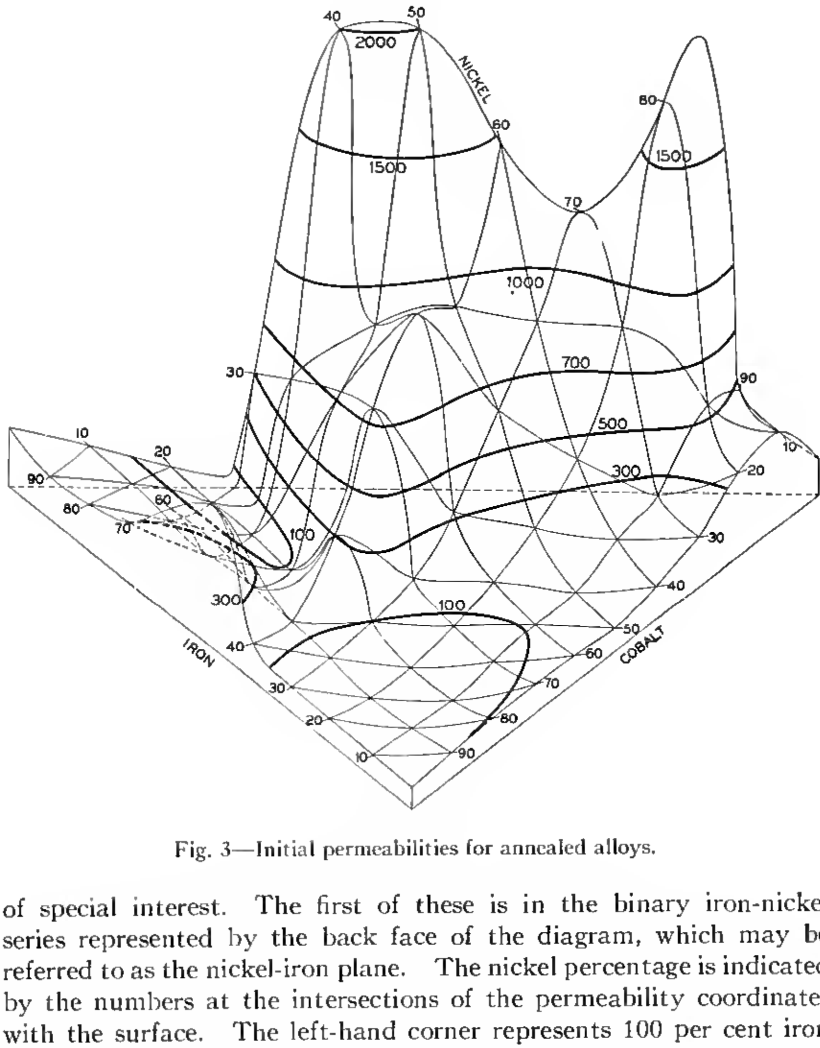

Fig. 3—Initial permeabilities for annealed alloys.

of special interest. The first of these is in the binary iron-nickel series represented by the back face of the diagram, which may be referred to as the nickel-iron plane. The nickel percentage is indicated by the numbers at the intersections of the permeability coordinates with the surface. The left-hand corner represents 100 per cent iron and the right-hand corner 100 per cent nickel, with initial permeabilities of 250 and 200, respectively. Between these limits of composition

the initial permeability varies from approximately 100 to more than 2,000. With small additions of nickel to iron, the permeability drops gradually until the added amount is approximately 28 per cent of the composition. From that point there is a rapid rise in the permeability

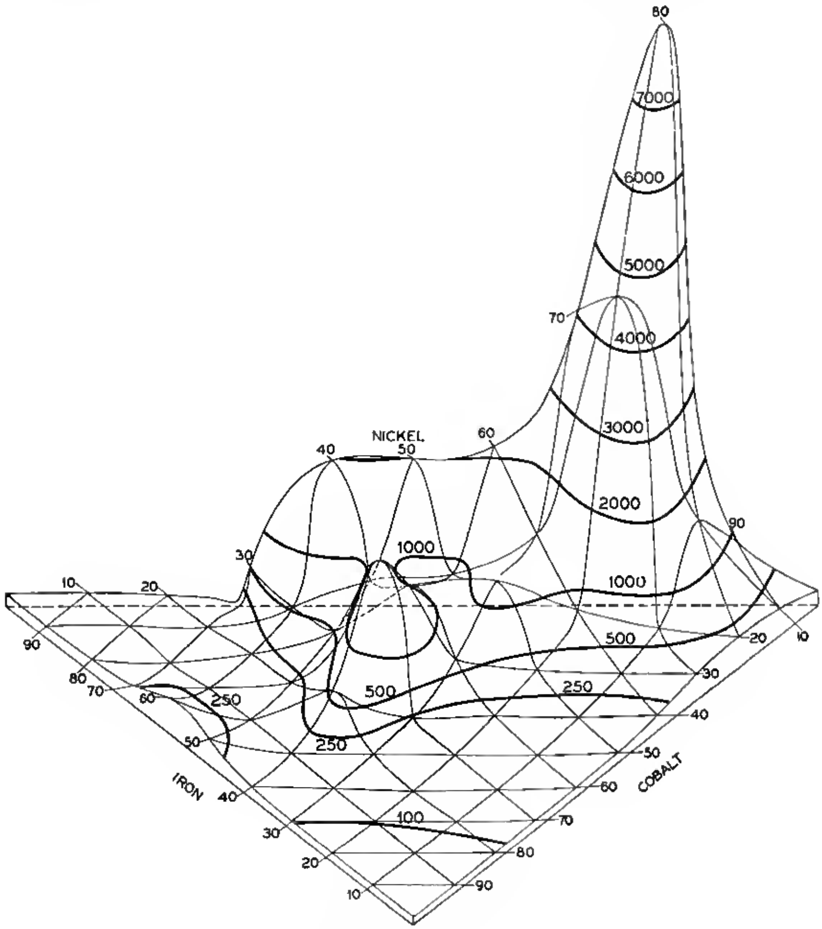

Fig. 4—Initial permeabilities for air-quenched alloys.

with the increase in the nickel content reaching a maximum of over 2,000 for the alloy containing approximately 45 per cent nickel. It then decreases as more nickel is added, reaching a second minimum of about 1,200 for 70 per cent nickel and increases again reaching a second maximum of approximately 1,900 at 83 per cent nickel.

Another region of special interest is found in the ternary series in

front of the first maximum in the nickel-iron series. If you follow the coordinate from 40 per cent nickel, you will note an elevation between the 700 and 1,000 permeability contour lines. The ternary alloys of this region are remarkable, not because of their high permeabilities although they are higher than for the surrounding region, but because of the constancy of permeability and low hysteresis loss at low magnetizing forces.

Another region of interest is located in the iron-cobalt plane between 40 per cent and 70 per cent iron. This is the plane in the figure on which the iron percentages are marked. The initial permeability for the highest point is over 600, more than twice the initial permeability of Armco iron.

When the alloys are air quenched, the initial permeabilities change in some regions very materially and give us an entirely different looking solid diagram as shown in Fig. 4. Because of the very high values of the permeabilities a different scale was used in this figure from that used in Fig. 3. It is interesting to note how the rapid cooling has affected some of the binaries in the iron-nickel plane. The rise in permeability begins at about 28 per cent, the same as for the annealed alloys, and the initial permeabilities are substantially the same, up to about 45 per cent nickel. Between 45 per cent and about 90 per cent nickel, the permeabilities have increased to a remarkable degree. The valley we saw in the region 45–75 per cent nickel for the annealed alloys has disappeared, and from 55 per cent upward there is a rapid increase reaching a peak value of approximately 8,000 for the composition containing $78\frac{1}{2}$ per cent nickel, an increase of over four times the permeability of the annealed alloy of the same composition.

Air quenching also increases the initial permeabilities of the group of ternary alloys which in the annealed condition showed a maximum characterized by a low hysteresis loss and a substantially constant permeability. This increase in permeability, however, is accompanied by a material increase in the hysteresis loss at low flux densities and a decrease in the constancy of permeability.

In contrast to the alloys just discussed, the iron-cobalt series in the neighborhood of 50 per cent iron gives a lower permeability upon rapid cooling. In this respect they behave the same as iron and cobalt.

The maximum permeabilities for the annealed alloys shown in Fig. 5 give a surface very similar to that for the initial permeabilities. The most interesting difference is the rapid decrease in permeability of iron as indicated at the left-hand corner of the diagram by the

addition of small amounts of cobalt or nickel, 10 per cent of either being sufficient to reduce the maximum permeability 85 per cent. All of the iron-nickel alloys between 35 per cent and 85 per cent nickel have as high or higher permeability than Armco iron.

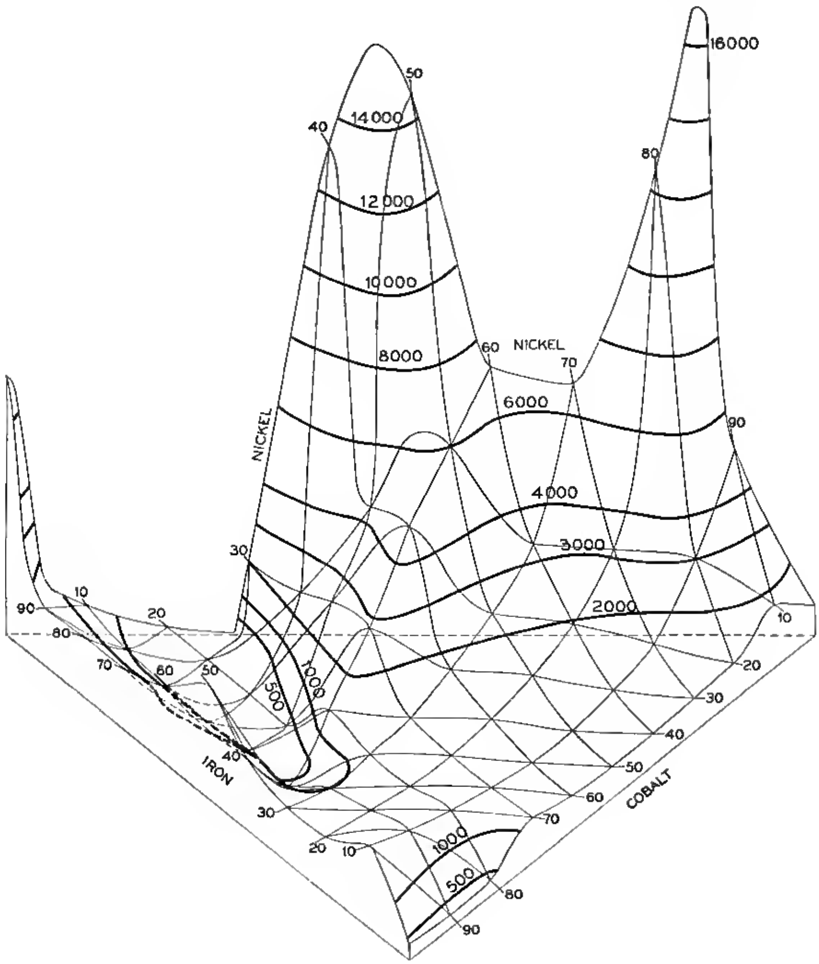

Fig. 5—Maximum permeabilities for annealed alloys.

I have not prepared a diagram for the maximum permeabilities for the air-quenched alloy. However, I can say that the surface obtained resembles the one shown for the initial permeabilities for the rapidly cooled alloys, although, of course, the maximum permeabilities are of different magnitudes. As high as 120,000 has been obtained for the alloy containing 78.5 per cent nickel.

The group of alloys of high permeability for low magnetizing forces in the iron-nickel series we have named permalloy.[2] The permalloys, therefore, include nickel-iron alloys containing more than approximately 30 per cent nickel. In referring to specific compositions in this group we have found it convenient to use as a distinguishing prefix for each composition its nickel content. For example, 78.5 permalloy is the alloy containing 78.5 per cent nickel and 21.5 per cent iron. When other elements are added to the permalloys, the chemical symbol and the percentage of the added element are also added to

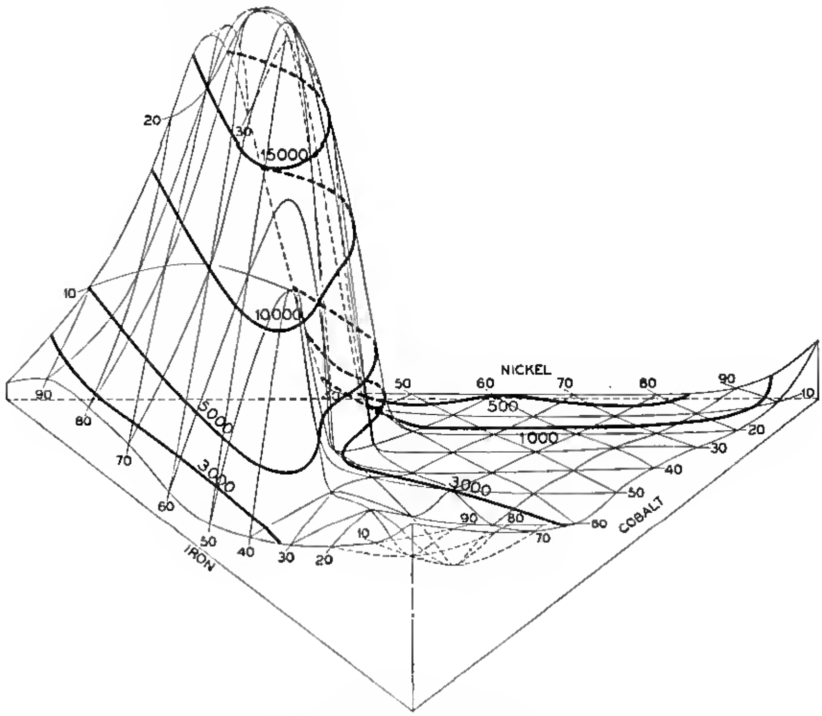

Fig. 6—Hysteresis losses, ergs per cm.[3] per cycle, for maximum flux density of 5,000 gauss for annealed alloys.

the prefix. For example, 3.5–78.5 Mo-permalloy is an alloy containing 3.5 per cent molybdenum, 78.5 per cent nickel, and 18 per cent iron.

The ternary alloys of constant permeability and extremely low hysteresis loss at low flux densities we have also grouped together under a common name, perminvar.[3] The limits of composition for the perminvars are less easily defined than for the permalloys, because the transition in magnetic properties is not as marked with small

[2] H. D. Arnold and G. W. Elmen, *Journal of Franklin Inst.*, May, 1923, p. 621.
[3] G. W. Elmen, *Journal of Franklin Inst.*, Sept., 1928, p. 317.

changes in composition. We have found that compositions between 10 per cent and 40 per cent iron, 10 per cent and 80 per cent nickel, and 10 per cent and 80 per cent cobalt have marked perminvar characteristics.

The hysteresis losses of the alloys in the annealed condition are plotted in Fig. 6 for a maximum flux density of 5,000 gauss. This

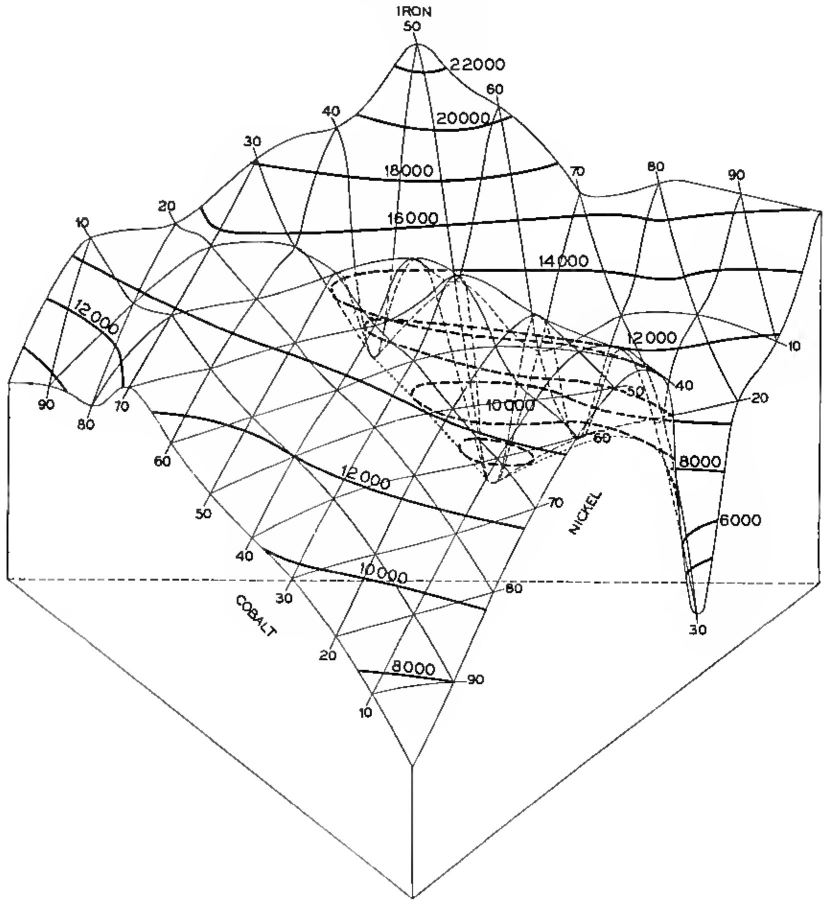

Fig. 7—Intrinsic inductions for annealed alloys at $H = 50$.

diagram illustrates again the abrupt change in the magnetic properties as we pass from alloys with large iron content to those in which nickel predominates. In this figure the lowest energy losses are those for alloys in the neighborhood of the 78.5 permalloy composition. In the iron-cobalt series the 50 per cent cobalt alloy has the lowest hysteresis loss.

The intrinsic inductions, which are those parts of the inductions contributed by the magnetic material, are shown in Fig. 7 for a magnetizing force of 50 gauss. In the figure the triangle has been turned through 120° clockwise from its position in the previous figures, placing the iron-cobalt alloys in the back of the diagram. For this

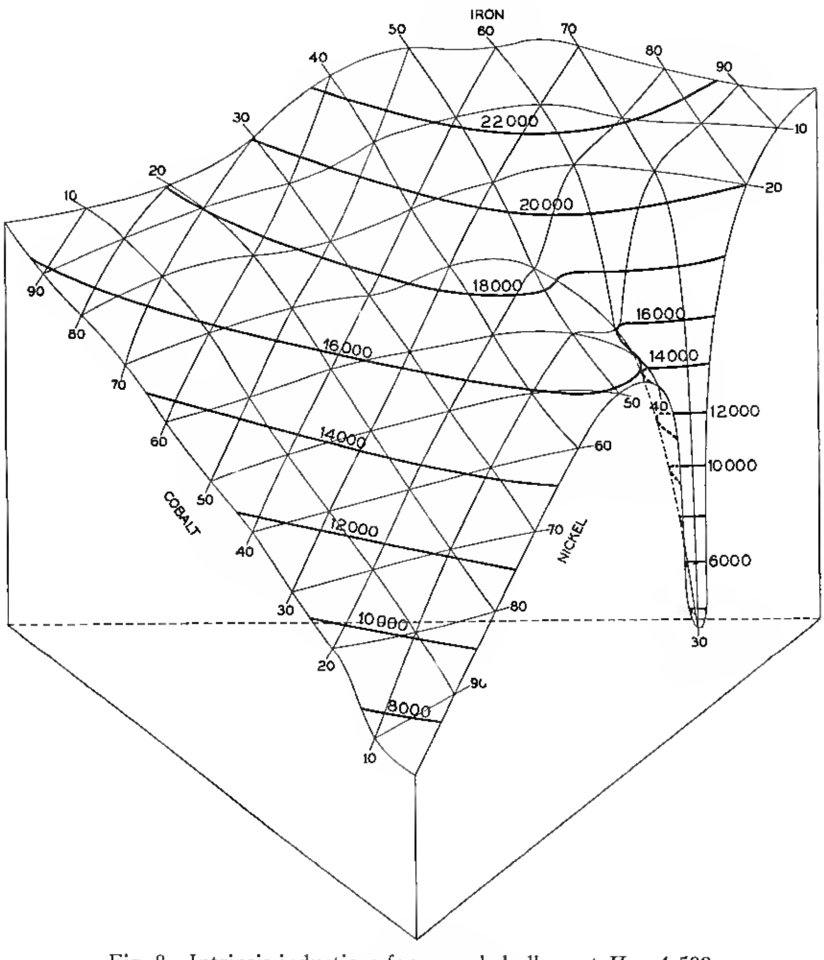

Fig. 8—Intrinsic inductions for annealed alloys at H = 1,500.

magnetization the 50 per cent iron-cobalt alloy is superior to any of the others.[4] Another interesting part of this diagram is the deep depression at about 30 per cent nickel, in the iron-nickel plane—now the right-hand front face of the diagram. This depression extends back for some distance into the ternary alloys.

[4] This was also found by Ellis, Engineering and Science Series No. 16, June, 1927, Rensselaer Polytechnic Institute.

The intrinsic inductions are also shown for a magnetizing force of 1,500 gauss in Fig. 8. Here we find that the irregularities of the surface in the previous figure have largely disappeared and the surface has become fairly flat. The inductions for the alloys in the neighborhood of 34 per cent cobalt and 66 per cent iron have now increased so that they are practically the same as for the 50 per cent composition.

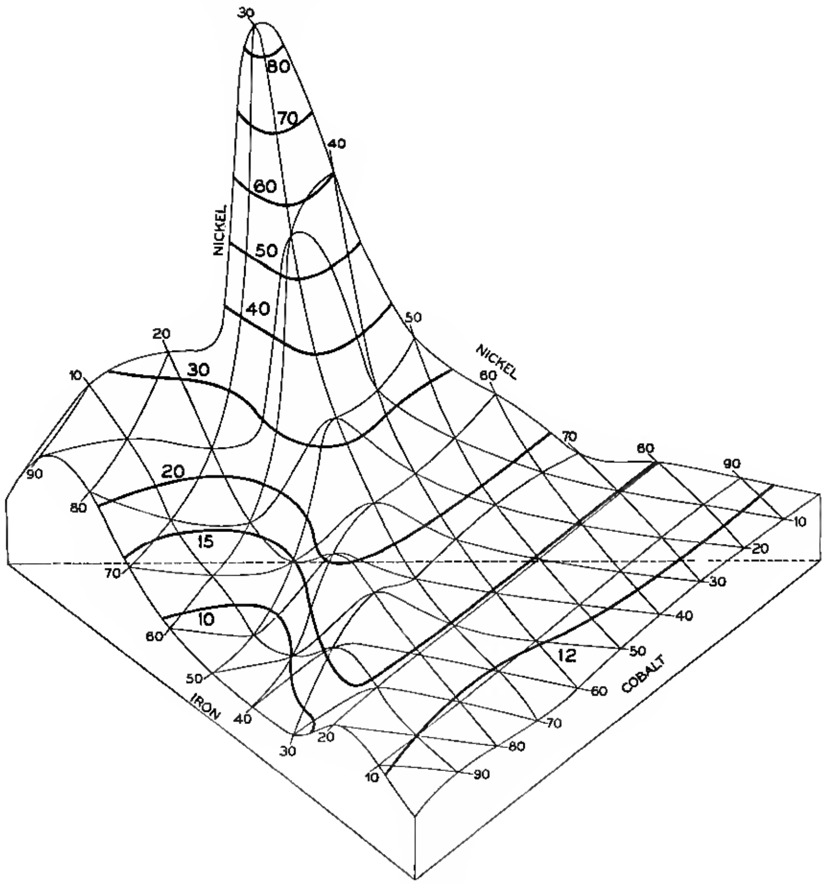

Fig. 9—Resistivities, microhm-cm., for annealed alloys.

The valley in the neighborhood of 30 per cent nickel has largely disappeared except for the alloys without cobalt which are much harder to saturate.

In Fig. 9 a solid diagram has also been constructed for the resistivity of these alloys in the annealed condition. It is interesting to note the high resistivities of some of the nickel-iron alloys—again in the

back of the diagram—and the low values for some of the cobalt-iron alloys in the 45–70 per cent cobalt range of compositions.

In the discussion of the magnetic properties of these alloys, I have pointed out that there are three regions of composition which are of special interest from the standpoint of applications because of their unusual magnetic properties. One of these is in the iron-cobalt series. A representative alloy of this group is the 50 per cent cobalt composition. In Fig. 10 the magnetization curves for this alloy and for

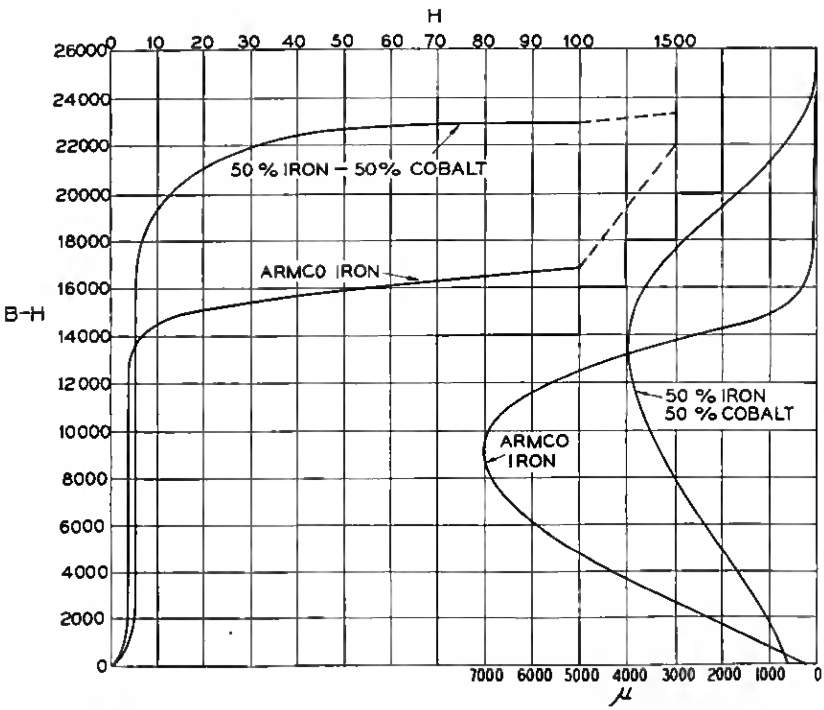

Fig. 10—Magnetization and permeability curves for the 50 per cent iron, 50 per cent cobalt composition and for Armco iron.

a sample of iron are shown on the left and the permeability curves plotted against the same scale of intrinsic inductions on the right. The scale for the magnetizing force of the magnetization curve is at the top of the figure. Below an induction of 1,000 and above 13,000 the permeability of the alloy is higher than for iron. Its initial permeability is 600 and the maximum permeability is 4,000. For a magnetizing force of 100 gauss the intrinsic induction is nearly 23,000 gauss. For Armco iron the initial and maximum permeabilities are 250 and 7,000, respectively, and the intrinsic induction for a magnetizing force of 100 gauss is 17,000.

The perminvars are the next group with interesting characteristics. Their remarkable constancy of permeability at low magnetizing forces and their extremely low hysteresis loss at low flux densities make them of unusual interest. The composition 45 per cent nickel, 25 per cent cobalt and 30 per cent iron is a typical alloy for this group. Permeability curves for this alloy for three types of heat treatment are plotted against magnetizing force in Fig. 11. The insert in the upper right-hand corner shows the lower parts of these curves plotted to a larger scale. For the baked alloy the permeability is constant at 300 with

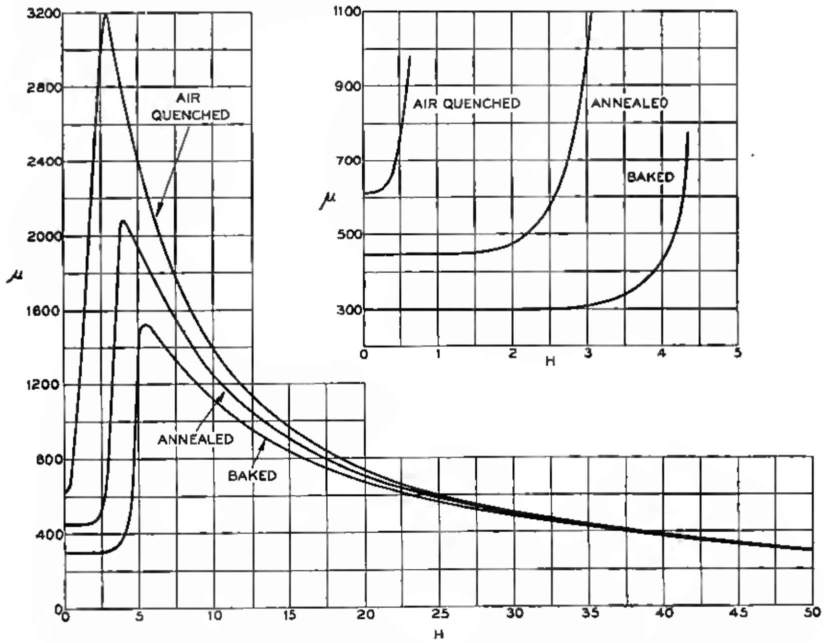

Fig. 11—Permeability curves for a perminvar alloy containing 45 per cent Ni, 25 per cent Co, 30 per cent Fe.

an increase of the magnetizing force from zero to $2\frac{3}{4}$ gauss. The initial permeability for the air-quenched alloy is more than twice that of the baked, but the constancy of permeability is a great deal less. This illustrates the close relation of these two properties. As the magnetizing force approaches 40 gauss the differences in the permeabilities, resulting from different rates of cooling, disappear.

The hysteresis loops for this composition are also of unusual interest. Fig. 12 illustrates the hysteresis characteristics for this alloy, in air-quenched and baked condition, for three maximum flux densities, 750, 1,000 and 5,000 gauss, respectively. For the lowest flux density of

the baked sample the ascending and the descending branches of the loop coincide and the loop is represented by a straight line. For the next higher flux density the loop, for the same heat treatment, begins to have a measurable area. At low values of induction, however, the two branches of the loop for the baked alloy approach each other and often come together completely at the origin. The complete loop for a maximum flux density of 5,000 gauss also shows this peculiar shape for the baked alloy. The loop is constricted in the middle, the two branches almost passing through the origin. The air-quenched alloy also shows tendency of constriction but much less than the baked. The areas of the two loops show that for this value of maximum flux

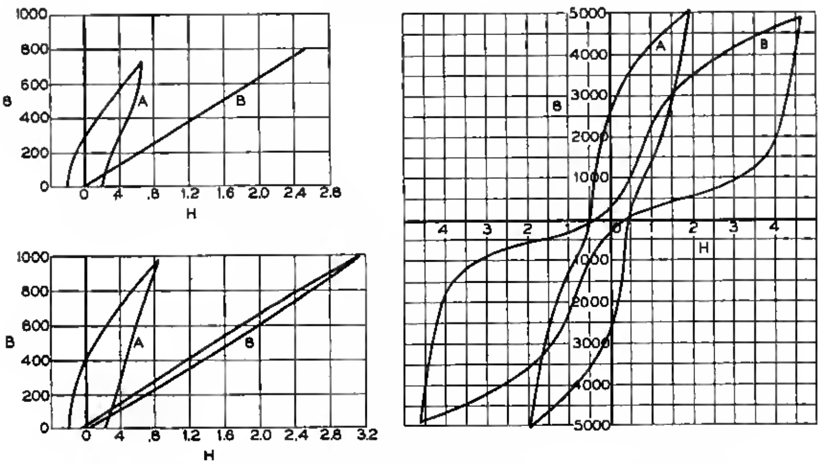

Fig. 12—Hysteresis characteristics for a perminvar alloy containing 45 per cent Ni, 25 per cent Co, 30 per cent Fe. A = air quenched; B = baked.

density the hysteresis loss for the baked sample is greater than for the air-quenched. This condition is the reverse of that for lower flux densities.

The last group of alloys of special interest are the permalloys. In Fig. 13 I have taken the curves for initial permeabilities of the iron-nickel series from the solid diagrams for the air-quenched and the annealed conditions and plotted them on the same scale of coordinates. A curve of initial permeabilities for a series of baked alloys is also plotted in this figure. The baking process for these alloys differed from the one we usually employed in that each alloy was baked until no decrease in the permeability resulted from further baking. For some alloys several weeks were required before this condition obtained. The time was shortest for compositions between 60 per cent and 80

per cent nickel. On both sides of this range the time necessary for stabilization increased both with increasing and decreasing nickel content. With nickel content of less than 42 per cent and more than 88 per cent, approximately, no difference sufficiently large to be attributed to the baking could be observed, even after the alloys had been baked for several weeks.

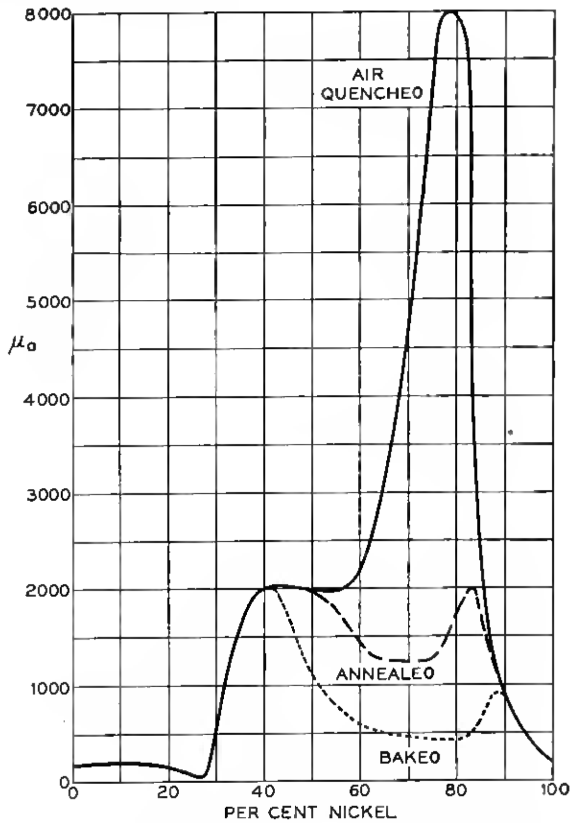

Fig. 13—Initial permeabilities for the Fe-Ni series.

The 78.5 permalloy composition in this series is of special interest because this alloy when air quenched gives the highest initial and maximum permeabilities. The magnetization curves for this composition are plotted in Fig. 14 for annealed and air-quenched samples, and for a sample of annealed iron. The lower part of this graph is shown in the insert on a larger scale. The curves are plotted for magnetizing forces between 0 and 10 gauss only. In these curves

the induction for the annealed sample remains lower than for the air-quenched sample, but as the force increases there is a tendency for the two curves to approach each other. This continues with still further increase in the magnetizing force and beyond 50 gauss the two curves coincide.

The permeability curves for these samples are plotted in Fig. 15, illustrating the great difference in their maximum permeabilities. For the annealed and the air-quenched samples, the initial perme-

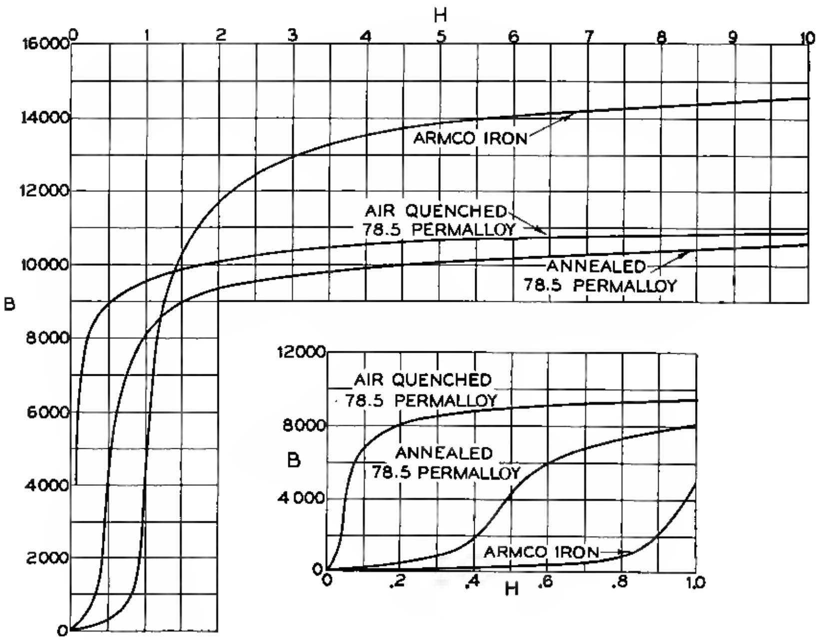

Fig. 14—Magnetization curves for 78.5 permalloy and for Armco iron.

abilities are 2,000 and 9,000, and the maximum permeabilities 10,000 and 87,000, respectively. The initial and the maximum permeabilities for the iron sample are 250 and 7,000, respectively.

The effect of air quenching on the energy loss is illustrated in Fig. 16 in which hysteresis loops for a maximum flux density of 5,000 gauss are plotted for the air-quenched and the annealed samples. The energy loss for the rapidly cooled sample is only 35 per cent of that for the annealed.

In deciding on a rate for air quenching we selected the rate which gave the highest initial permeability for the 78.5 permalloy. In Fig. 17 I wish to illustrate how small changes in this rate affect the initial

and the maximum permeabilities for this composition. The scale for maximum permeability is on the left and for initial permeability on the right. The cooling rate is in degrees centigrade per second. It is interesting to note that the highest initial permeability was obtained

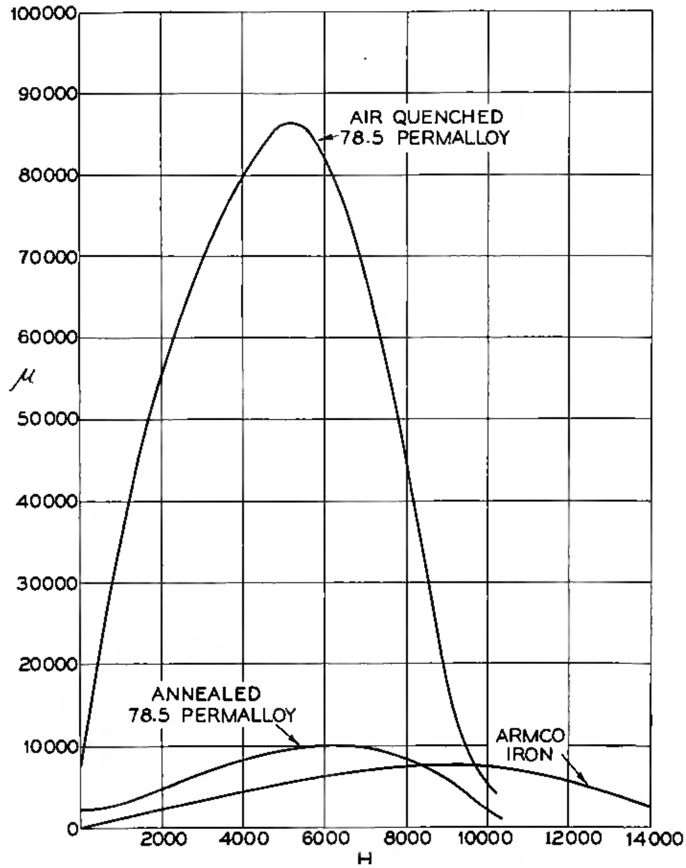

Fig. 15—Permeability curves for 78.5 permalloy and for Armco iron.

when the cooling rate was approximately 20° C. per second, while a rate four times as rapid gave the highest maximum permeability. Ten thousand and 120,000 were the highest initial and maximum permeabilities, respectively, for these particular samples. These values are not the highest we have obtained for this composition. Test samples from other castings have given as high as 13,000 for initial permeability and upwards of 400,000 for maximum.

Fig. 18 illustrates the manner in which the permeability at a low magnetizing force for a rapidly cooled 78.5 permalloy composition is affected by passing it through a temperature cycle between room temperature and 650° C. The permeability was measured for a constant magnetizing force of .003 gauss as the temperature was passed through this cycle. The rate at which the sample was heated and

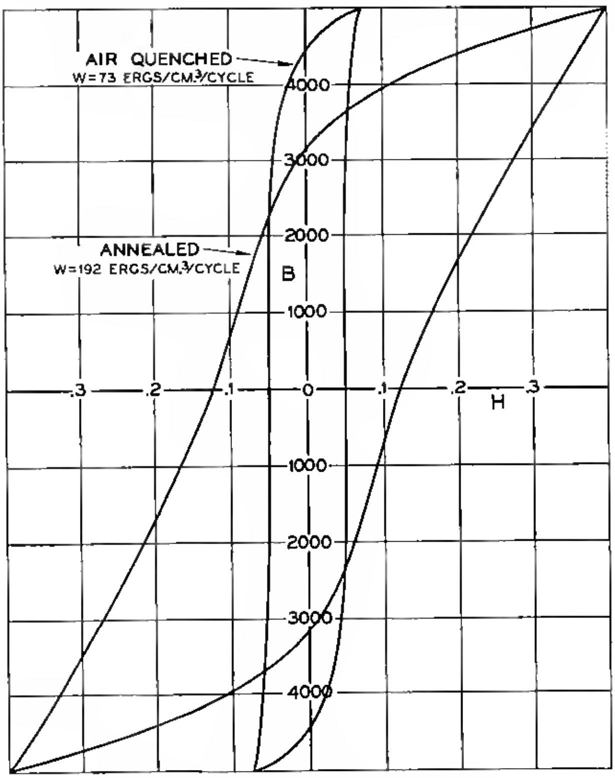

Fig. 16—Hysteresis loops for 78.5 permalloy.

cooled was rather slow, requiring upwards of two hours to complete the heat run.

The permeability of the air-quenched sample was 7,000 at the start, increasing rapidly up to about 315° C. With further increase in temperature there is a rapid drop in permeability until 500° C. is reached. With further increase in temperature the permeability rises very rapidly to a sharp peak at about 530° C. and then decreases, the alloy becoming non-magnetic at 590° C. With decreasing temperature the alloy again becomes magnetic at about the same temperature, at

which the magnetism disappeared and the curve for decreasing temperature is the same as for increasing temperature over a short range. At 500° C. the curve for decreasing temperature does not follow its original path but continues to drop until the temperature reaches about 425° C. From that point on until room temperature is reached the return curve is nearly horizontal.

At room temperature the permeability is only 2,000, a drop of 5,000 from its value at the beginning of the run. With the alloy in this condition, if a second cycle is run, the permeability both for increasing

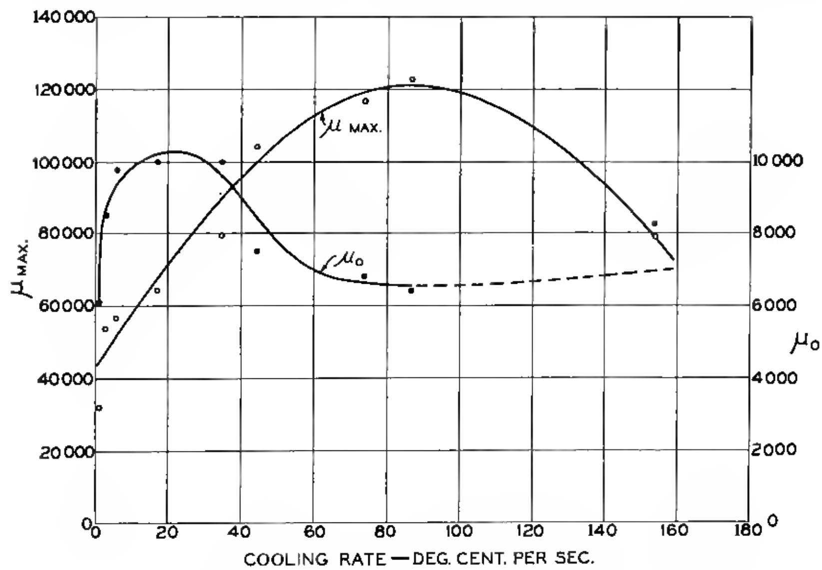

Fig. 17—Initial (μ_0) and maximum (μ_{max}) permeabilities for 78.5 permalloy for different rates of air quenching from 600° C.

and decreasing temperature will be substantially the same as the one in the figure for decreasing temperature. By heating the sample to 600° C. and air quenching, the magnetic properties at the beginning of the test are restored.

The connection between the permeability of this composition and the heat treatment in the temperature range below 600° C. is also illustrated by a series of tests in which annealed rings were air quenched from temperatures below 600° C. The rings were placed in a furnace and heated at 600° for 15 minutes. The temperature was then decreased slowly to 550° C. and held until the alloys had reached a constant condition. One of the samples was then taken out of the furnace and air quenched. The temperature of the furnace was then

dropped another step and the process of stabilization and air quenching repeated for the next ring. This was repeated for a number of temperatures until there was substantially no change between two rings quenched from successive temperatures. Another series of annealed rings was slowly heated in successive steps to the same temperatures, stabilized, and then air quenched.

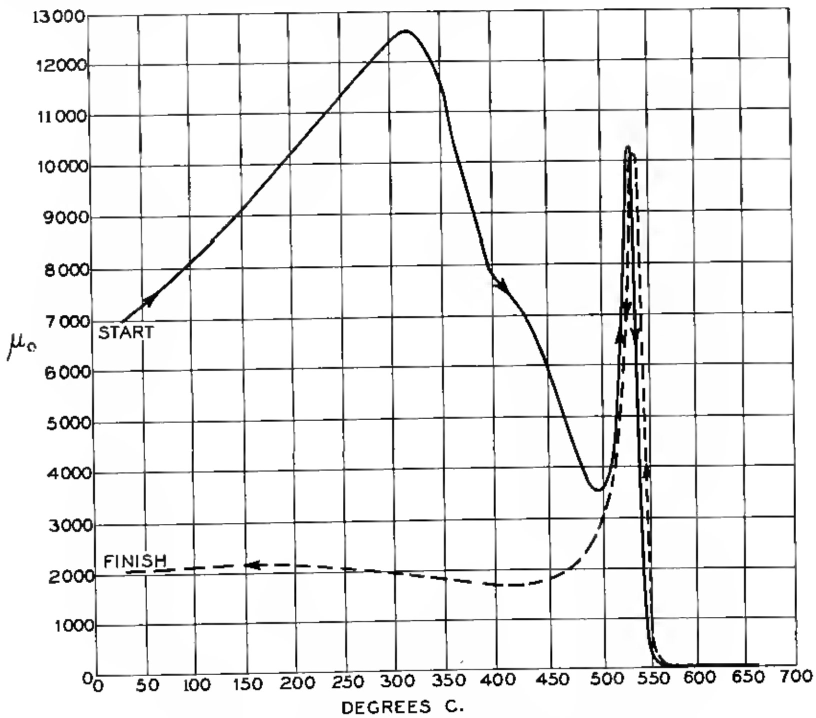

Fig. 18—Temperature-permeability curve for 78.5 permalloy: magnetizing force .003 gauss.

A comparison of the initial permeabilities of these rings showed that each ring attained a definite permeability, characteristic of the temperature from which it was air quenched whether it reached that point from a lower or a higher temperature, provided it was stabilized before air quenching. The air quenched rings stabilized between 500° and 400° C. showed the greatest change in permeability. The time required for stabilization at the higher temperatures was very short, only a few minutes being required in the neighborhood of 500° C., but it increased progressively as the temperature was lowered, and in the lower end of the range several days were required for the alloy to reach a constant condition.

Tests on other compositions showed that those alloys in which the magnetic properties depended on the rate of cooling below 600° C. gave results similar to those for the 78.5 permalloy. The temperature range was also found to be substantially the same as for the 78.5 permalloy, although in some cases there were indications that small changes occurred above 600° and below 400° C.

This connection between heat treatment and magnetic properties led me to conclude that the differences in these properties in the alloys which had been heat treated differently below 600° C. were caused by constitutional changes in the alloys. Such changes are common in alloys in the solid state, often at low temperatures. The progressive change in the permeability as the temperature of the alloy decreases slowly below 600° C., the gradual increase in the time required for a change to complete itself as the temperature drops, and the prevention of the change by rapid cooling through this temperature range support this conclusion.

It is well known that some alloys are in the state of homogeneous solid solutions at high temperatures, but segregate into two or more phases as the temperature drops. Such segregation ordinarily takes place in a definite temperature range, and is progressive in nature. It is a change of this type which I picture as taking place in these alloys during slow cooling. At the upper end of the critical temperature range for each alloy, the homogeneous solid solution begins to segregate into constituents of different composition. This segregation continues until the temperature has dropped to a point where no further changes take place. Rapid cooling prevents this segregation and the alloys remain after cooling in a metastable condition.

We would suppose that if such a change takes place, confirmatory evidences might be found. I shall refer, briefly, to some of our attempts to obtain evidence to confirm our speculations as to the nature of these magnetic changes.

The resistivity was measured for rapidly cooled and for baked alloys both of permalloy and perminvar compositions. These measurements showed that for both types of alloys, baking reduced the resistivity. For example, the resistivity of a 78.5 permalloy sample was measured after baking and after air quenching. The resistivities for the two conditions were 14.2 and 15.8 microhm-cm., respectively. Upon rebaking the resistivity again dropped to 14.5, about the same as before it was air quenched. This change is in accordance with what would be expected if a segregation took place with annealing. A homogeneous solid solution has the highest resistivity and segregation tends to lower it.

Other interesting evidence is obtained from the study of the hysteresis loops. For the perminvar alloys the constricted loops are very marked and easily produced. In the permalloys containing between 60 and 80 per cent nickel also there is a tendency to constriction in the slowly cooled alloy, not so marked but sufficiently prominent to lead me to believe that the same general changes occur in both groups of alloys, differing only in the nature of the segregates and the ease with which segregation occurs. Now we know that homogeneous magnetic materials have a characteristic type of hysteresis loop. For such materials there is no constriction in the middle, but the widest part of the loop is generally at that point. We also can

a *b*

Fig. 19—Hysteresis loops: *a*, perminvar (45 per cent Ni, 25 per cent Co, 30 per cent Fe); *b*, bi-metallic rod. Loop traced with cathode ray oscillograph.

construct hysteresis loops which have constrictions by making up cores of several materials in a parallel or parallel-series arrangement.[5] This is illustrated by the hysteresis loop *b* in Fig. 19. This loop is traced by a cathode ray oscillograph for a bi-metallic rod, 15 in. long consisting of a core of .04 in. diameter unannealed piano wire and a .006 in. wall permalloy tube, heat treated to give high permeability and fitting closely to the wire. Curve *a* is a loop similarly traced for a perminvar core. Though the magnetic circuit conditions for the two cores are not the same, the marked similarity of the two loops favors the view that the constricted loop of the perminvar results from segregation.

It is interesting to note in this connection that the examination by X-ray crystal analysis methods of these alloys has not given evidence

[5] E. Gumlich, *Arch. f. Elektrotechnik*, Vol. 9, p. 153, 1920.

of a segregation such as other evidence leads me to think must occur. Perhaps the reason for this is that the different constituent metals are so closely related that small changes in the structure cannot be detected by this means, or perhaps the reason is that the size of the groups of atoms making up the constituents is too small to be detected by X-ray methods.

While the variation in the permeability and in the other magnetic characteristics which could be affected by heat treatment may be explained by the theory of segregation, this theory does not explain why these alloys have such high permeabilities at low magnetizing forces.

Nor does this theory explain the unexpected magnetic characteristics, such as high saturation values of induction, or the low electrical resistance which characterize a large proportion of the alloys in the iron-cobalt series. It has been suggested by Weiss [6] that when the saturation values of an alloy are higher than they are for the constituent metals, it is an indication of the existence of an intermetallic compound. On this ground he has accounted for the high saturation values he found for an iron-cobalt alloy containing 34 per cent cobalt. In our investigation, which was not carried up to the high magnetizing forces used by Weiss, the 50 per cent cobalt alloy gave us as high flux densities as any in the series for magnetizing forces upwards of 1,500 gauss.

It has been found in the study of intermetallic compounds that one indication of their existence is a low resistivity. It is generally believed that if an alloy has lower resistivity than any of its constituent metals, an intermetallic compound exists. In our measurements of the resistivity of the iron-cobalt series we found that the alloys with lowest resistance were those containing between 25 per cent and 60 per cent iron. There is a rather abrupt decrease in the resistivity as the percentage of iron increases beyond 25 per cent. Beyond 50 per cent iron there is a gradual increase with a maximum at about 85 per cent iron. From these measurements we would conclude that if an intermetallic compound exists, it is of a higher cobalt percentage than that suggested by Weiss. From our measurements of the resistivity of the alloys in this series the most probable intermetallic compound would be one containing approximately 66 per cent cobalt of the chemical formula $FeCo_2$.

The data which I have presented are those for the compositions of iron, nickel and cobalt. In addition to these alloys, we have studied the effects of adding non-magnetic elements to numerous alloys of

[6] *Transactions of the Faraday Society*, Vol. 8, p. 149.

particular compositions. I cannot at this time go into a detailed discussion of the results with these, but I shall mention briefly some of them. We found that the addition of some of the non-magnetic metals to both the permalloys and the perminvars made those alloys less sensitive to heat treatment. The resistivity was also generally increased. For some compositions the addition in small percentages

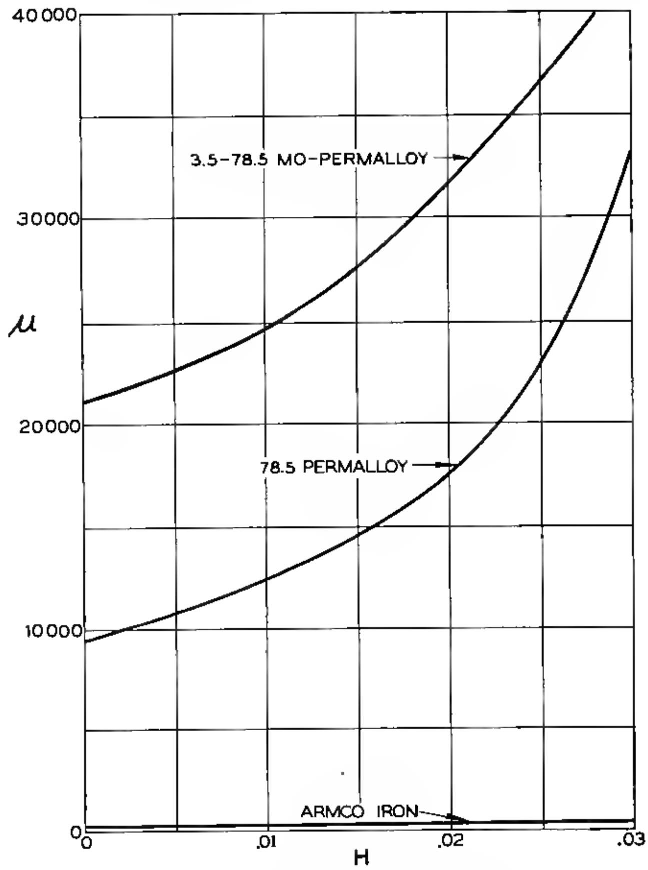

Fig. 20—Permeability curves for permalloys.

of a non-magnetic metal, particularly chromium and molybdenum, increases the permeability at low magnetizing forces. This is illustrated in Fig. 20 where I have plotted the permeability curves for Armco iron, 78.5 permalloy, and a 3.5–78.5 Mo-permalloy. You will note that the initial permeability of the molybdenum-permalloy alloy is 21,000 as compared with 9,000 for the permalloy without

molybdenum. As a rule the maximum permeability was generally decreased when a non-magnetic element was added and so were the saturation values of induction.

As our investigation was undertaken primarily for the purpose of searching for magnetic materials which could be used to advantage in the electrical communication field, it may be of interest to describe a few of the principal uses to which some of these alloys have been put.

Of the three groups of alloys which are of special technical interest, the permalloys are now used extensively in electrical communication circuits. Perhaps its most spectacular use is for continuous loading of submarine telegraph cable.

The term loading is used in the electrical communication art to designate a system of adding inductance to a transmission circuit for the purpose of overcoming the unfavorable transmission characteristics resulting from the electrical capacity of the circuit. This system has

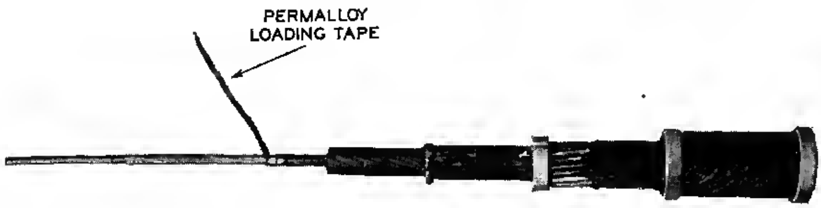

Fig. 21—Sample of submarine loaded cable, showing the loaded conductor.

been used in telephone transmission circuits for over a quarter of a century. The standard method used for telephone circuits, in which inductance coils are placed at equally spaced intervals along the transmission line, was not considered practical for deep sea cables. The only suitable method from a mechanical standpoint was a continuous loading in which a magnetic material is distributed uniformly along the whole length of the cable. Before permalloy was developed the best magnetic material available was iron. It could not be used economically for long submarine cables because of its low permeability. With permalloy having between 40 and 50 times the permeability of iron in the range of magnetic field strength encountered in such cables, it was found that beneficial results could be attained and cables of more than five times the carrying capacity of the old type could be built.

The first permalloy loaded submarine telegraph cable was laid in 1924 between New York and the Azores, a distance of approximately 2,300 nautical miles. A sample of the deep sea section of this cable

is shown in Fig. 21. Numerous other loaded cables have been laid since 1924; the total mileage of loaded submarine telegraph cables is now upwards of 16,000 nautical miles.

Another purpose for which permalloy is now used extensively is for loading coils for telephone transmission circuits. Before the introduction of permalloy, finely powdered, insulated and compressed iron dust was used for the cores of these coils. Permalloy has now replaced iron for loading coil cores, and upwards of a million cores per year are used by the Bell System.[7] For these cores the permalloy is used in the form of compressed insulated powder. Some of the advantages in using permalloy result from its lower hysteresis losses and higher permeability. Taking advantage of these qualities in the design of the coils, it has been possible to reduce materially their

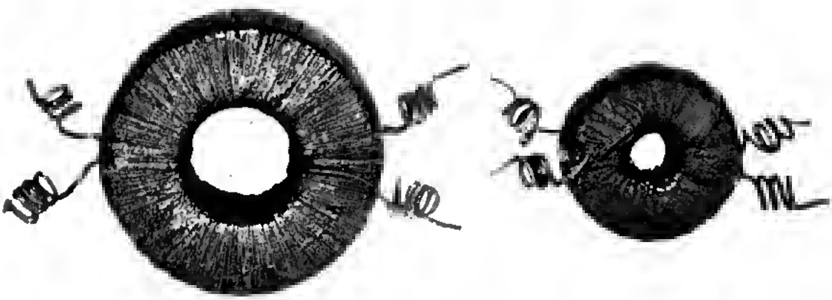

Fig. 22—Compressed powdered core loading coils: left, electrolytic iron core; right, permalloy core.

sizes. This is illustrated in Fig. 22 where two standard loading coils for use in the same circuits are shown. One of these has a permalloy core and the other a core of iron. The former is approximately one-third of the size of the latter.

When these coils are used in service usually a large number are placed in containers which are placed at different points in vaults or on poles along the telephone circuits. In Fig. 23 two such iron cases with their cable connecting stubs are shown; each contains 200 coils. The small case contains the permalloy coils, and the large case the iron core coils. The use of permalloy has reduced the combined weight of the coils and the cases from approximately 1,700 lbs. to about 700 lbs.[8]

[7] The use of permalloy core loading coils is increasing very rapidly. Recent figures show that approximately 2,000,000 of these coils will be required by the Bell System per year during the next few years.

[8] The decreased size of the coils and containers has resulted in a very substantial saving in the cost of loading.

Another use of permalloy in the telephone plant has been found in the case of relay cores. Relays are used to connect and disconnect mechanically the telephone circuits at the central office and at other points. These relays are magnetically operated and their efficiency depends largely on the magnetic quality of the core material. Certain groups of these relays are required to operate under very severe circuit conditions where the operating currents are small and where

Fig. 23—Cast-iron cases each containing 200 loading coils: left, permalloy core coils; right, iron core coils.

the relays are required to distinguish between very small changes in current values. For such circuits, relays with permalloy cores are now used extensively.

The permalloy alloys are also used extensively for cores in high quality audio transformers, in telephone receivers and earphones, and in electrical measuring instruments.

The permalloy series was first developed, and is also the one which

was first used, for commercial purposes on a large scale. The other alloys are still in the commercial development stage, but interesting results have been obtained which make us feel confident that both the perminvars and the iron-cobalt alloys will take their places beside permalloy as important magnetic materials in electrical communication.